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A SHROUDED FLOW ARC AIR HEATER FOR SIMULATION OF A 250 MEGAWATT PLASMA JET HEATER

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ABSTRACT

A 50 Lbm/sec shrouded flow arc air heater producing the pressure field and centerline temperature of a 250 MW plasma jet heater has been developed for reentry missile nose tip testing.

INTRODUCTION

The requirement for higher performance ballistic reentry vehicles has placed greatly increased demands on thermal protection techniques. One of the primary tools for screening and developing improved heat protection methods and materials has been the high pressure - high temperature arc plasma jet. These facilities normally employ a supersonic ($M = 1.5$ to 2.0) high stagnation pressure air plasma flow to duplicate the pressure and heating rates experienced in flight. However, the power required for uniform test flows large enough for full scale model tests is in excess of 200 megawatts to the gas which is far greater than present arc heater capabilities.

Since the cost of large power supplies is discouraging and a long heater development cycle would be required, other means were investigated by AFFDL for producing or simulating the large arc heated flows required. The goal of this effort was to develop an arc air heater from the AFFDL 50 MW unit which would provide simulation of a 250 megawatt plasma jet heater.

Development Procedure

The Air Force Flight Dynamics Laboratory's 50 Megawatt RENT (Re-Entry Nose Tip) Arc Heater (Reference 1) represented a large stride toward this goal by extending powers from the 10 megawatt level to 50 megawatts at pressures of 125 atmospheres and total temperatures of 14,000 $^{\circ}$R. This heater, shown schematically in Figure 1, produced 1.11 inch diameter Mach 1.8 test jets with model stagnation pressures up to 100 atmospheres. Although this capability has proven most useful for sub-scale testing, it still falls short of the power levels required for full scale models in uniformly heated arc jets.

The approach taken in this effort was suggested by J. P. Doyle (Reference 2) and by tests in the peaked heating rate profiles shown in Figure 2 from Reference 1. These tests showed that for low angles of attack ($\alpha = 0$ to 6^{o}) on axisymmetric bodies the stagnation point and body heating rates were governed by the hot core flow when the model was centered in the test jet. This led to the possibility that large high-power uniformly-heated test flows might be simulated for most axisymmetric missile nose tip tests by surrounding a much smaller arc jet with a large cold air shroud flow if a uniform pressure field in the test region could be maintained. The approach taken during these tests was to introduce a large (up to 45 lbm/sec) cold air flow into the 50 Megawatt RENT Arc Heater just ahead of its sonic throat as shown in Figure 3, and to size and configure the throat to pass the cold and hot air flows simultaneously without mixing. This cold shroud air was injected subsonically with a large tangential component to generate a large stabilizing radial pressure gradient in the turbulent shear layer which divides the hot core and cold shroud flow to inhibit mixing of the two flows.

Shrouded Arc Heater Performance

A series of tests were conducted over a wide range of mass ratios $\left(\text{i.e. } \frac{\dot{m}_{shroud}}{\dot{m}_{hot\ flow}}\right)$.

Figure 4 shows the performance of the shrouded arc heater versus the standard RENT heater at the nozzle design mass ratio of 8:1 and an arc current of 2600 amps. This condition produced an effective throat size of $d^* = .900$ inches for the hot core with the design shroud throat diameter of 1.60 inches. Performance of the shrouded heater is nearly identical with the standard heater at the design point.

A series of "off-design" tests with mass ratios from 3.5 to 9.5 produced the effective hot core throat sizes shown in Figure 5 with the 1.60 inch nozzle at $P_o = 100$ atmospheres and an arc current of 2600 amps. These effective throat diameters were determined by the method of Reference 3. Typical arc heater operating characteristics at mass ratios (M.R.) of 4, 6 and 8 are shown in Figure 6. No difficulty was experienced in operating the shrouded heater over a wide range of mass ratios and pressures with the 1.60 inch throat.

Typical test section profiles at the 2.125 inch nozzle exit diameter are shown in Figure 7 from Reference 4 for M.R. = 5.95. A centerline total enthalpy of 6320 BTU/lbm was calculated from heating and pressure measurements using the method of Reference 5. The pressure field at the exit appears to duplicate that of a uniformly heated 1200 psi jet.

Considering heaters of the same efficiency and defining the following for the conditions of Figure 7:

$$\text{Shrouded Arc Heater Power} = Ps_{arc} \approx 35 \text{ Megawatts}$$

$$\text{Shroud Factor} = Fs = \frac{\text{shrouded throat area}}{\text{unshrouded throat area}}$$

$$= \left(\frac{1.6}{.9}\right)^2 = 3.160$$

$$\text{Unshrouded Flow Enthalpy Peaking Factor} = Fp = \frac{H_o \text{ centerline}}{H_o \text{ average}}$$

(From Reference 1)

$$\approx 2.0$$

$$\text{Flared Nozzle Factor} = Ff = \frac{\text{flared nozzle exit area}}{\text{non-flared nozzle exit area}}$$

(For an undisturbed test flow - See Reference 6) $= 1.160$

We see that the arc heater power required to produce an equivalent uniform jet is:

$$P_{equivalent} = Ps_{arc} \text{ X } Fs \text{ X } Fp \text{ X } Ff$$

$$= 35 \text{ MW X } 3.16 \text{ X } 2.0 \text{ X } 1.160$$

$$= 256 \text{ Megawatts}$$

Comparison of the measured heating and pressure profiles in Figure 7 indicate that the shrouded arc heater operating at 35 Megawatts effectively duplicates the pressure field and centerline total enthalpy of a 250 Megawatt arc heater producing a uniform jet.

Summary and Future Plans

The AFFDL Shrouded Flow Arc Heater with a peaked enthalpy profile and flared nozzle has successfully duplicated the pressure field and centerline temperatures of a 250 Megawatt uniformly heated arc heater operating at 108 atmospheres total pressure.

Basic operating characteristics of the unshrouded arc heater may be maintained if the shrouded heater nozzle throat is sized to accomodate the normal hot flow plus the cold shroud flow. Also, a wide range of "off-design" mass flow ratio conditions may be run with no significant heater operating difficulties. The lower mass ratios gave the maximum heater voltage, hot core mass flow, and model heating rates with little or no degradation of the test jet pressure field or hot core size.

The Shroud Flow Arc Heater is a novel method of meeting the extremely large test flow requirements for full scale ground tests of missile heat protection systems, representing a considerable economy over the power required for a uniformly heated arc jet.

Future plans include development of larger higher pressure shroud flow systems for the AFFDL RENT Facility.

REFERENCES

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6. Huber, Franz J. A. and Van Kuren, James T., "Flared Nozzle for Testing Missile Nose Tips in the AFFDL 50 MW Re-Entry Nose Tip Facility", Paper Presented at 35th Semi-Annual Meeting of Supersonic Tunnel Association.

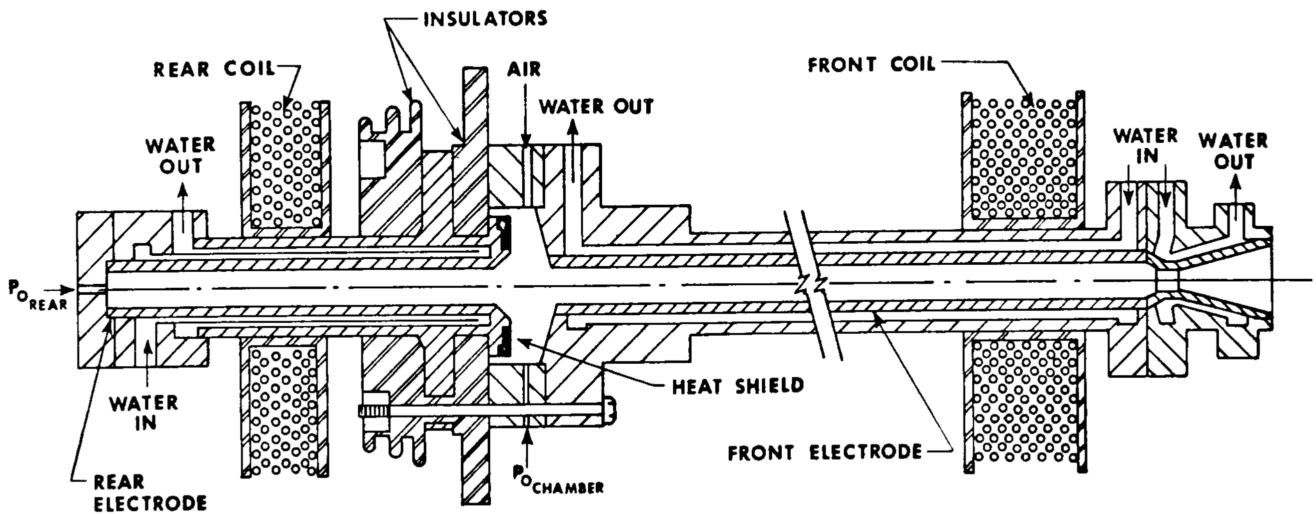
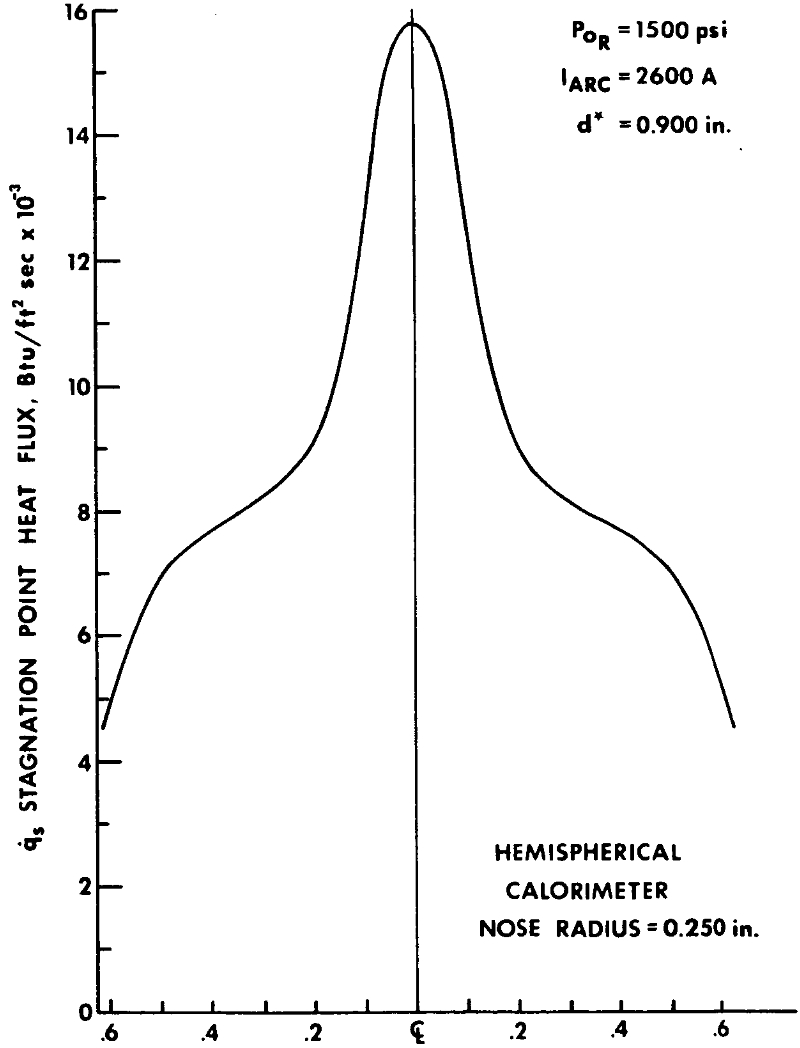


FIGURE 1. 50MW RENT ARC HEATER SCHEMATIC



RADIAL DISTANCE FROM NOZZLE ℄, inches
Axial Station 0.100 from Exit Plane

FIGURE 2. HEAT FLUX PROFILE OF CONTOURED RENT NOZZLE WITH STANDARD ARC HEATER

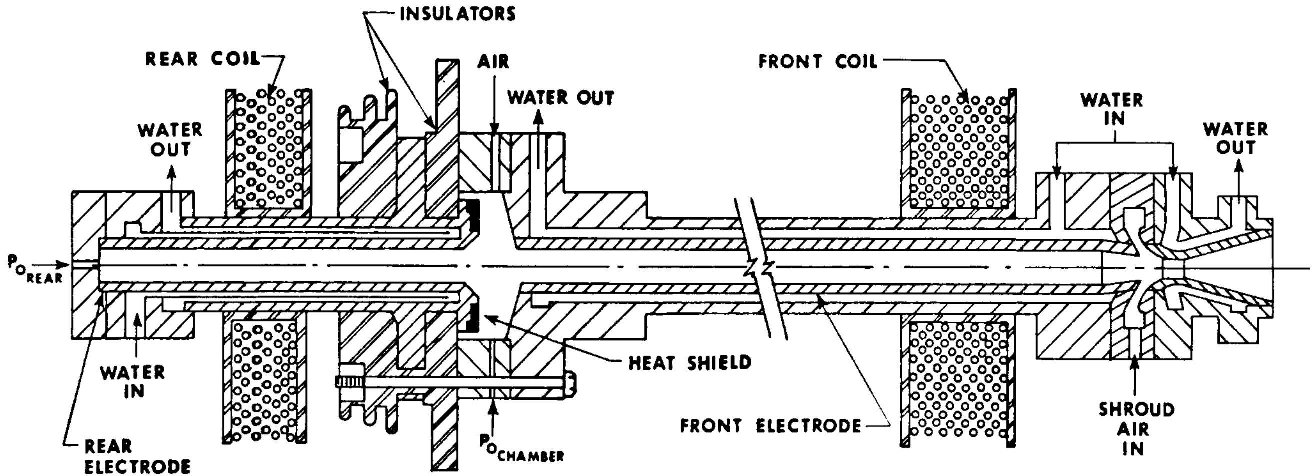


FIGURE 3. SHROUDED FLOW ARC HEATER

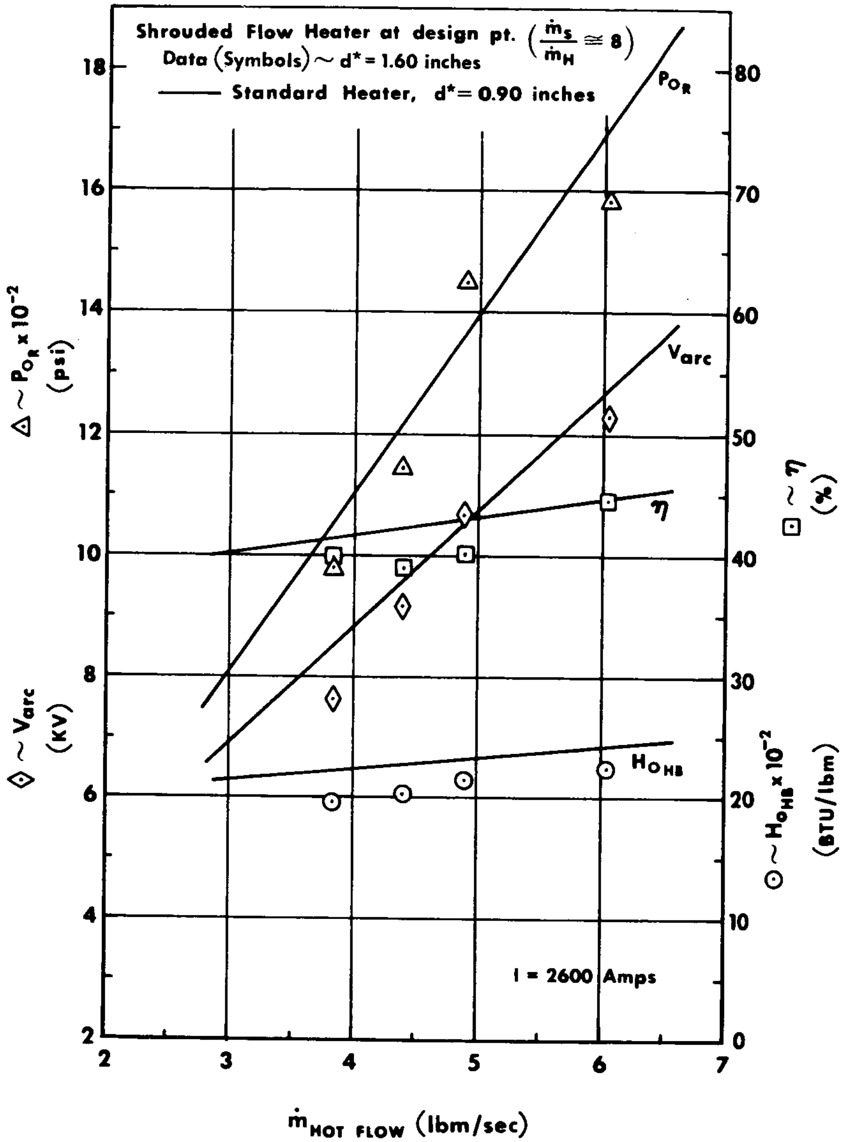


FIGURE 4. ARC HEATER OPERATING CHARACTERISTICS STANDARD AND SHROUDED FLOW

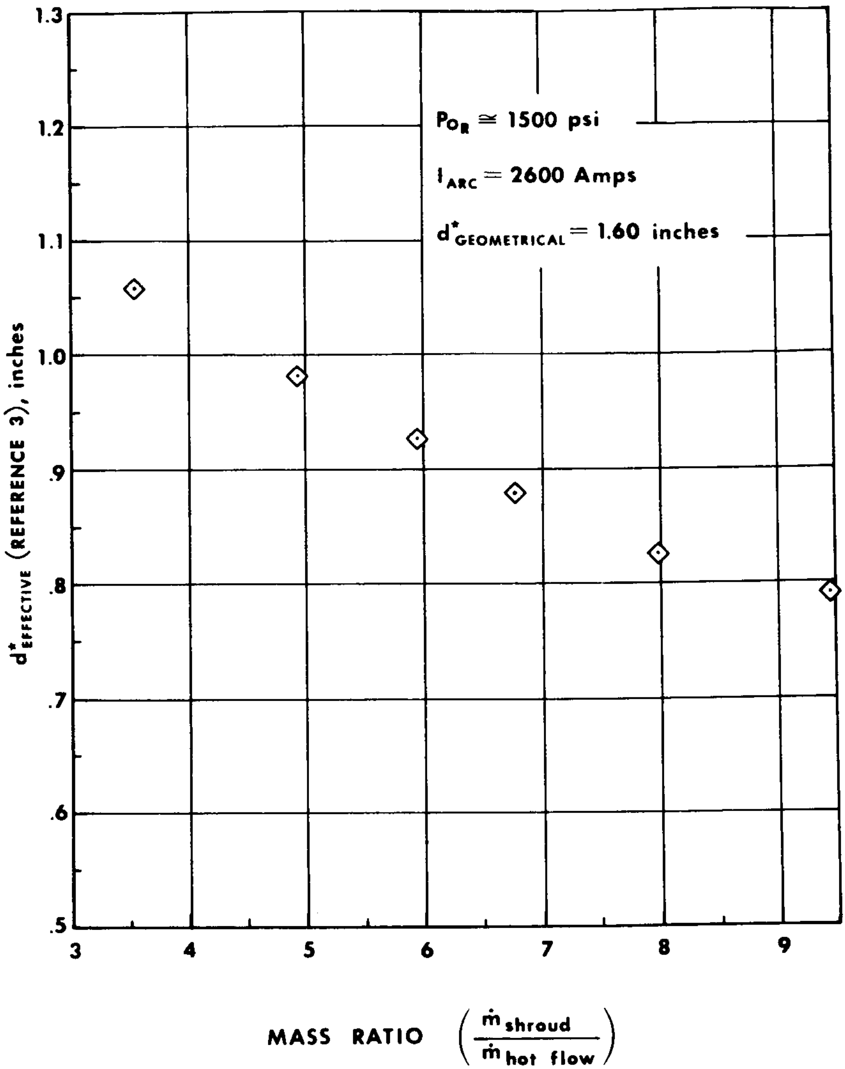


FIGURE 5. EFFECTIVE HOT FLOW THROAT SIZE (d^*_{EFF}) FOR VARIOUS MASS RATIOS IN SHROUDED ARC HEATER

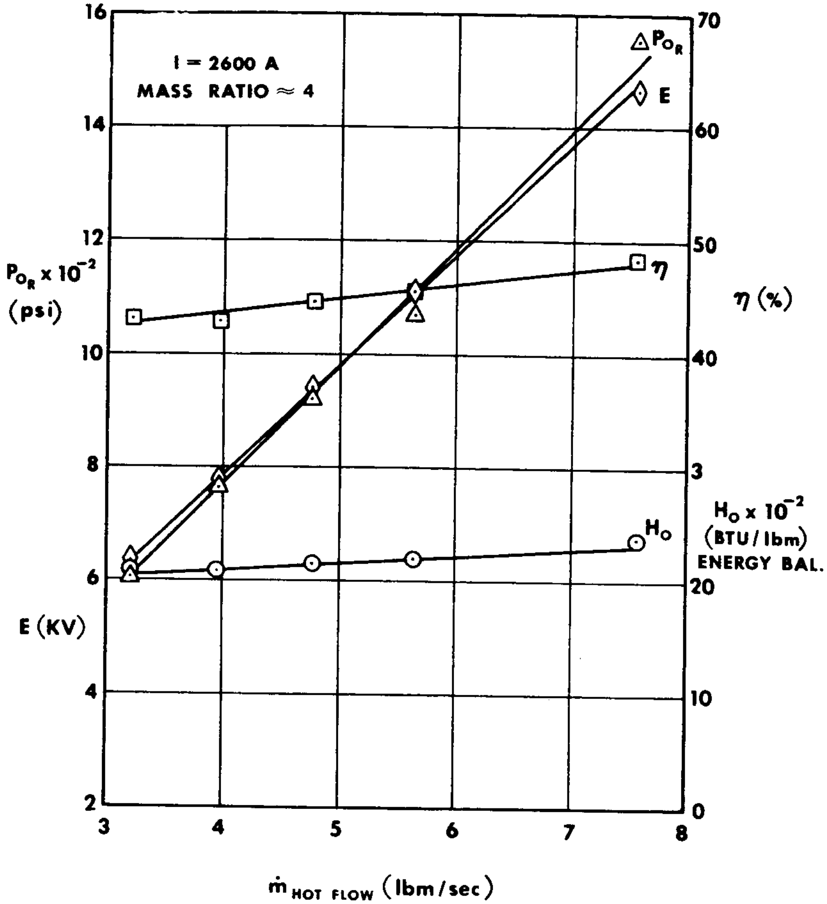


FIGURE 6a. SHROUD FLOW ARC HEATER OPERATING CHARACTERISTICS FOR CONSTANT MASS RATIO

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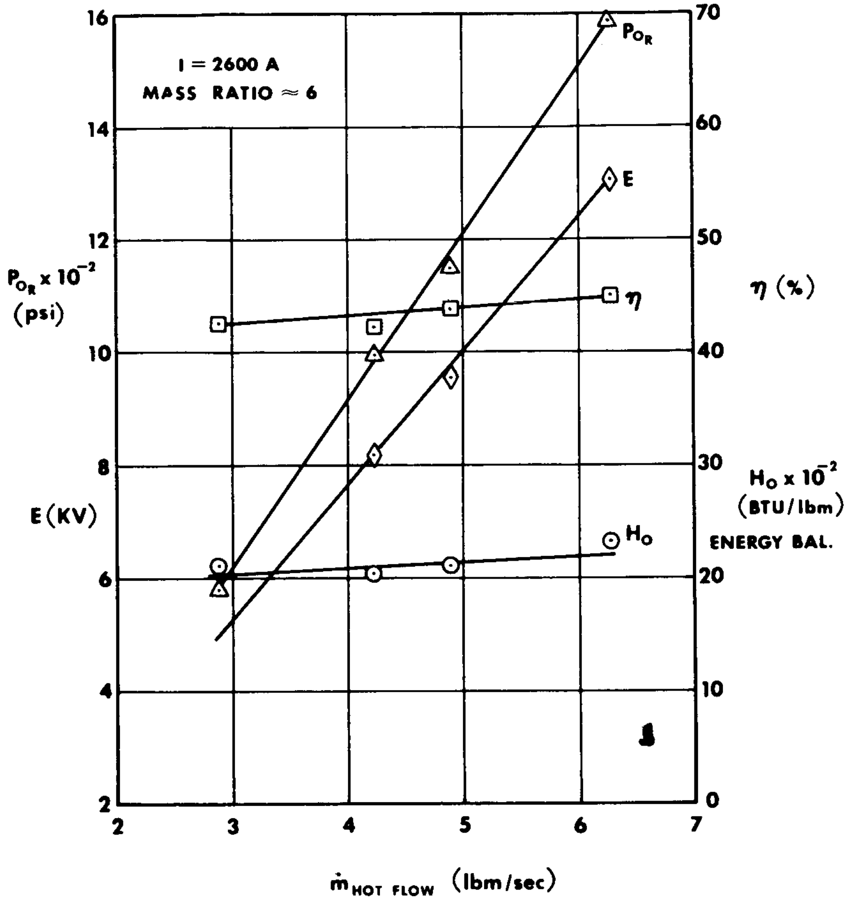

FIGURE 6b. SHROUD FLOW ARC HEATER OPERATING CHARACTERISTICS FOR CONSTANT MASS RATIO

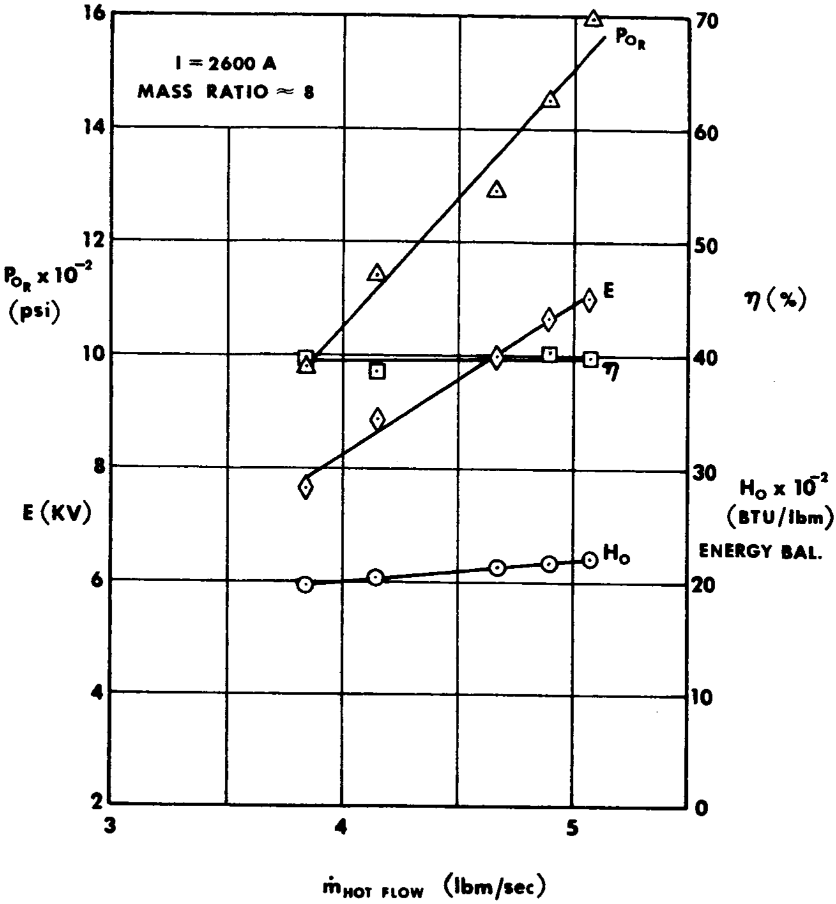

FIGURE 6c. SHROUD FLOW ARC HEATER OPERATING CHARACTERISTICS FOR CONSTANT MASS RATIO

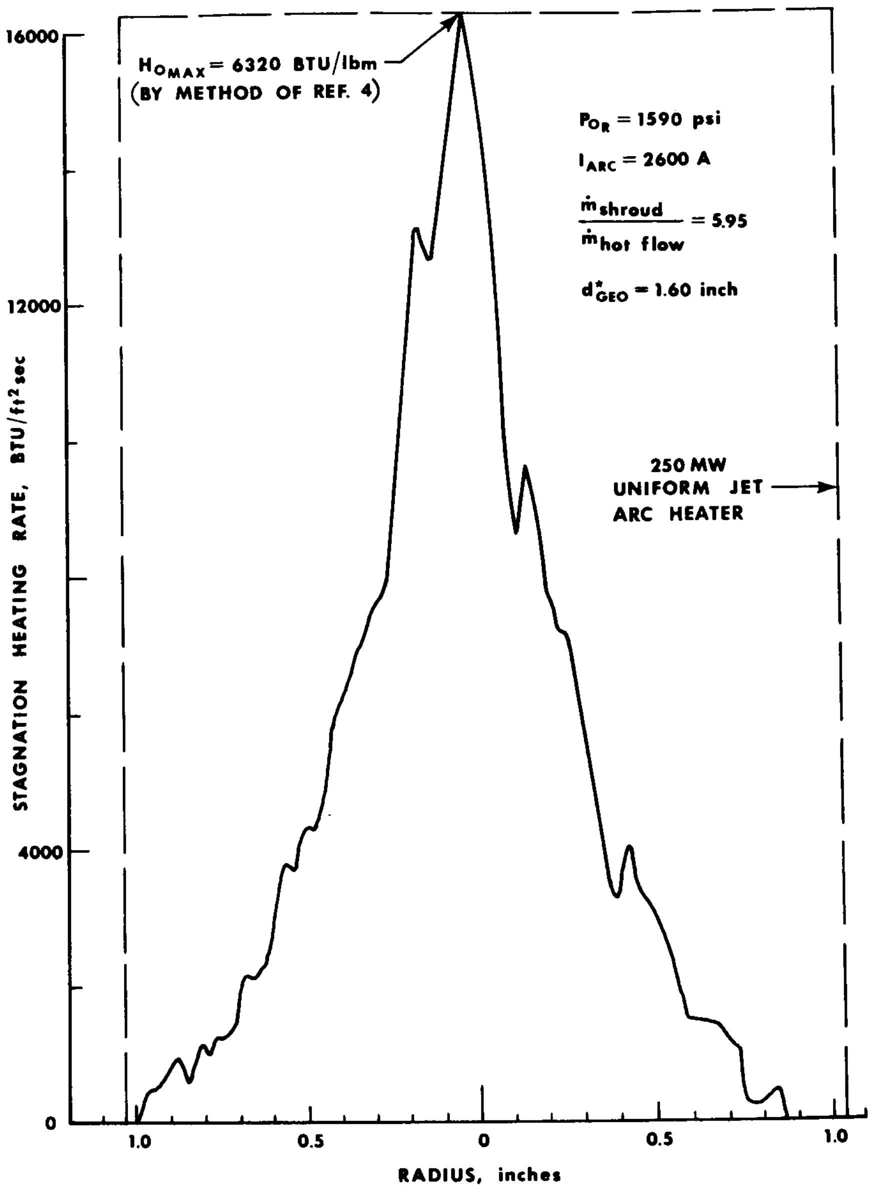

FIGURE 7a. RADIAL HEAT FLUX PROFILE FOR SHROUDED FLOW ARC HEATER WITH 2.125 INCH EXIT DIA. NOZZLE

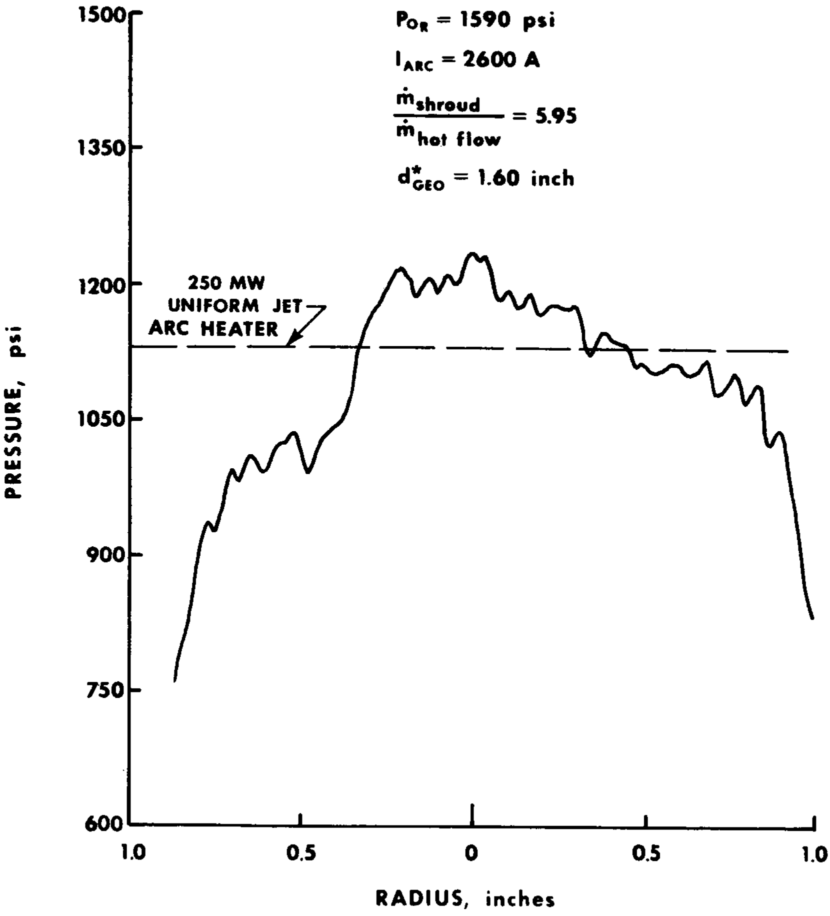

FIGURE 7b. RADIAL PRESSURE PROFILES AT X = 0.1" FOR SHROUDED FLOW ARC HEATER WITH 2.125 INCH EXIT DIA. NOZZLE